AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 107:137–142 (1998)

Technical Note: Modeling Primate Occlusal Topography Using Geographic Information Systems Technology

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KEY WORDS GIS; GRASS; primate dental morphology

ABSTRACT Most functional analyses of primate tooth form have been limited to linear or area measurements. Such studies have offered but a limited glimpse at differences in occlusal relief among taxa. Such differences in dental topography may relate to tooth function and, so, have considerable implications for the inference of diet from fossil teeth. In this article, we describe a technique to model and compare primate molars in three dimensions using Geographic Resources Analysis Support System (GRASS) software. We examine unworn lower second molars of three extant hominoids with known differences in diet (*Gorilla gorilla*, *Pan troglodytes*, and *Pongo pygmaeus*), and two fossil forms, (*Afropithecus turkanesis* and *Dryopithecus laietanus*). First, we obtained approximately 400 landmarks on the occlusal surfaces of each tooth using an electromagnetic digitizer. Raster “terrain models” of occlusal surfaces were then created by interpolation of the coordinate data. We used GRASS terrain analysis automated techniques to quantify the volumes and slopes of individual cusps. We also used the GRASS watershed technique to identify the volume of liquid that would accumulate in each tooth’s basin (a measure of basin area), and the directions and intensity of drainage over the occlusal surface. In sum, GRASS shows considerable potential for the characterization and comparison of tooth surfaces. Furthermore, techniques described here are not limited to the study of teeth, but may be broadly applicable to studies of skulls, joints, and other biological structures. Am J Phys Anthropol 107:137–142, 1998. © 1998 Wiley-Liss, Inc.

INTRODUCTION

Numerous studies have shown that tooth form can be used to predict aspects of diet and feeding behavior in living primates. Most such studies have thus far been limited to linear or area measurements. While these have been very useful for functional analyses, many are limited in their ability to reflect occlusal relief and to depict teeth as three-dimensional objects. This study presents a new method to characterize and allow the comparison of primate teeth in three dimensions using Geographic Resources Analysis Support System (GRASS) software.

Most quantitative studies of primate molar functional anatomy have involved analyses of the lengths of shearing crests. Kay (1984), for example, devised a shearing quotient to compare shearing crest lengths and, to a degree, occlusal relief among primates. He found that folivores and insectivores have longer shearing crests than do frugivores. Further, among frugivores hard-object

Received 12 May 1998; accepted 1 June 1998.

Contract grant sponsor: LSB Leakey Foundation; Contract grant sponsor: NSF; Contract grant number SBR 9601766.

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feeders have shorter crests (and blunter teeth) than do soft-fruit eaters. This association between crest length and diet holds for all major extant primate groups: strepsirrhines, platyrrhines, cercopithecoids, and hominoids (see Ungar [1998] for review). Such studies have important implications for paleobiology, as they suggest that molar morphology also likely reflects diet in fossil primates.

Still, workers have begun to recognize that even more detail about diet might be gleaned from teeth given new computer-driven methods for modeling surfaces in three dimensions (e.g., Ungar et al., 1994). Geographic Information Systems (GIS) provide one promising method for modeling dental topography (e.g., Reed, 1997).

GIS were developed to apply the power of computers to solving environmental and infrastructural problems. Today, they are used for everything from 911 emergency vehicle routing to assessing the habitat of endangered species. Many GIS tools have been created to examine and model the physical surface of the Earth. These tools offer equal potential for examination and analysis of other physical surfaces, such as the occlusal surfaces of primate teeth.

GRASS is a public-domain GIS written by the US Army Construction Engineering Laboratory, Champaign, IL (Westervelt et al., 1987). GRASS was originally created as a tool for analysis and management of large-scale environmental issues, but its vast suite of terrain analysis tools and programming "toolbox" structure make it suitable for many more tasks than originally intended. Analysis in GRASS is primarily performed on data in a raster format, consisting of two-dimensional matrices where each cell, or value, records some attribute of a surface at a particular location. These cells might contain the original z value from digitizing, or they may indicate slope, aspect (direction of slope), or any other characteristic or index value. Each theme, such as elevation or slope, is stored as an individual raster layer. GRASS supports simple three-dimensional point data in what is called a "sites" format.

In this article, we demonstrate how GRASS can be used to interpolate an occlusal surface, and to gather data on volume, slope, and aspect of individual cusps. Further, we show how GRASS tools, such as the r.watershed command, can be used to generate important new categories of data, including the volume of liquid that would accumulate in each tooth's basin (a measure of basin area), and the directions and intensity of drainage over the occlusal surface.

TABLE 1. Slope and volume values for specimens included in this study*

	Afro-pithecus	*Dryo-pithecus*	*Gorilla*	*Pan*	*Pongo*
Average slope					
Hypoconulid	42.21	23.75	47.33	41.73	40.1
Hypoconid	40.49	20.71	51.5	42.21	33.91
Protoconid	32.7	33.23	38.72	34.71	27.89
Metaconid	33.53	23.25	38.08	30.78	43.2
Entoconid	40.36	37.73	41.36	42.73	41.2
Cusp Volume					
Hypoconulid	3.54	0.5	16.94	1.75	3.58
Hypoconid	3.06	0.8	6.74	1	0.8
Protoconid	0.3	0.54	2.03	0.55	0.95
Metaconid	0.29	1.02	1.66	0.7	2.53
Entoconid	2.33	6.15	5.32	4.14	4.04
Basin Volume	0.04	0.27	0.23	0.76	8.02

* Cusp slope values are in degrees, and volumes are in mm^3.

METHODS AND RESULTS

High-resolution replicas were taken of original unworn lower second molars of the extant hominoids *Gorilla gorilla*, *Pan troglodytes*, and *Pongo pygmaeus*, and the fossil Miocene catarrhines *Afropithecus turkanesis* and *Dryopithecus laietanus*. The living taxa cover the spectrum of dietary adaptations of extant great apes, including the more folivorous *Gorilla* and the frugivores *Pan* and *Pongo*.

High-resolution molds of each specimen were prepared using a polyvinylsiloxane dental impression putty (Coltene, Inc., Mawath, NJ). Casts were poured with an epoxy resin and catalyst (Tap Plastics, Inc., Dublin, CA).

Data collection

Data were collected using a Polhemus 3Draw Pro (Polhemus Inc., Colchester, VT) electromagnetic digitizer. This consists of a tablet and stylus that allow the user to trace the occlusal surface of a specimen, recording x, y, and z coordinates. Specimens were placed at the center of the tablet for consistency, with the buccal side facing the x axis. Approximately 400 coordinates were col-

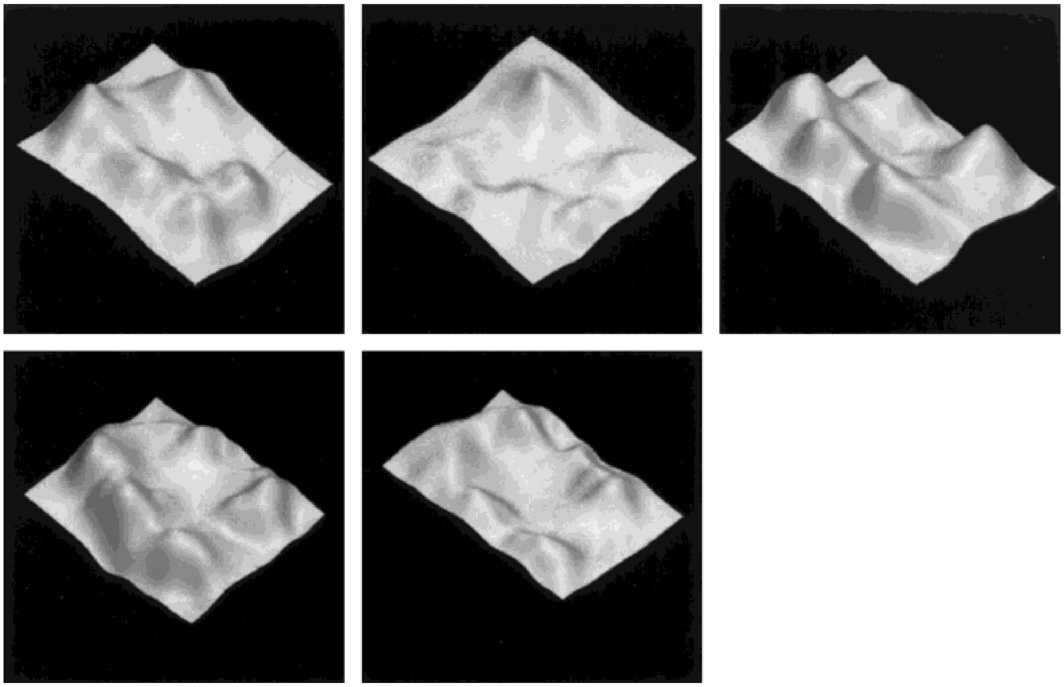

Fig. 1. Surface models of teeth examined in this study (upper left to lower right): *Afropithecus, Dryopithecus, Gorilla, Pan, Pongo.*

lected for each surface at a rate of 70 points per minute to a resolution of 0.13 mm. The digitizer was attached to a PC microcomputer, and coordinates of each point were stored as ASCII files using the 3Draw software (Polhemus Inc., Colchester, VT).

The resulting ASCII files were imported into GRASS 4.1, running on a Sun SparcServer 690. Where single x,y coordinates were recorded more than once, resulting z values were averaged through a UNIX shell script specifically created for the task. Duplicate records were also parsed to a second file, so that they could be readily inspected for possible data collection errors.

Interpolation

Once the unique records were converted to a GRASS sites file, they were interpolated to create a continuous raster layer of z values. We tested several interpolation algorithms, including inverse-distance weighting and kriging (a geostatistical method) for their ability to accurately fit the known data points. The most satisfactory results were achieved using a GRASS program called s.surf.tps, which is based on a thin-plate splining model (Mitasova and Hofierka, 1993). This program simulates draping a membrane over the known points. By changing the spline tension, the behavior of the membrane may be altered from that of a flexible rubber sheet to a thin metal plate. Other parameters used in this study include smoothing, minimum interpolation distance, and minimum number of points for interpolation. It was found that the best results were achieved with a fairly low spline tension (tension = 20) and a small amount of smoothing (smooth = 2) (see Fig. 1).

Individual cusp characterizations

First, contour lines and slope data were computed for the entire surface of each tooth. We identified individual cusps by selecting the lowest elevation contour lines that fully surrounded those cusps. The areas defined by the contour lines were then used to isolate slope and elevation raster cells for each cusp (Fig. 2). Volume and average slope

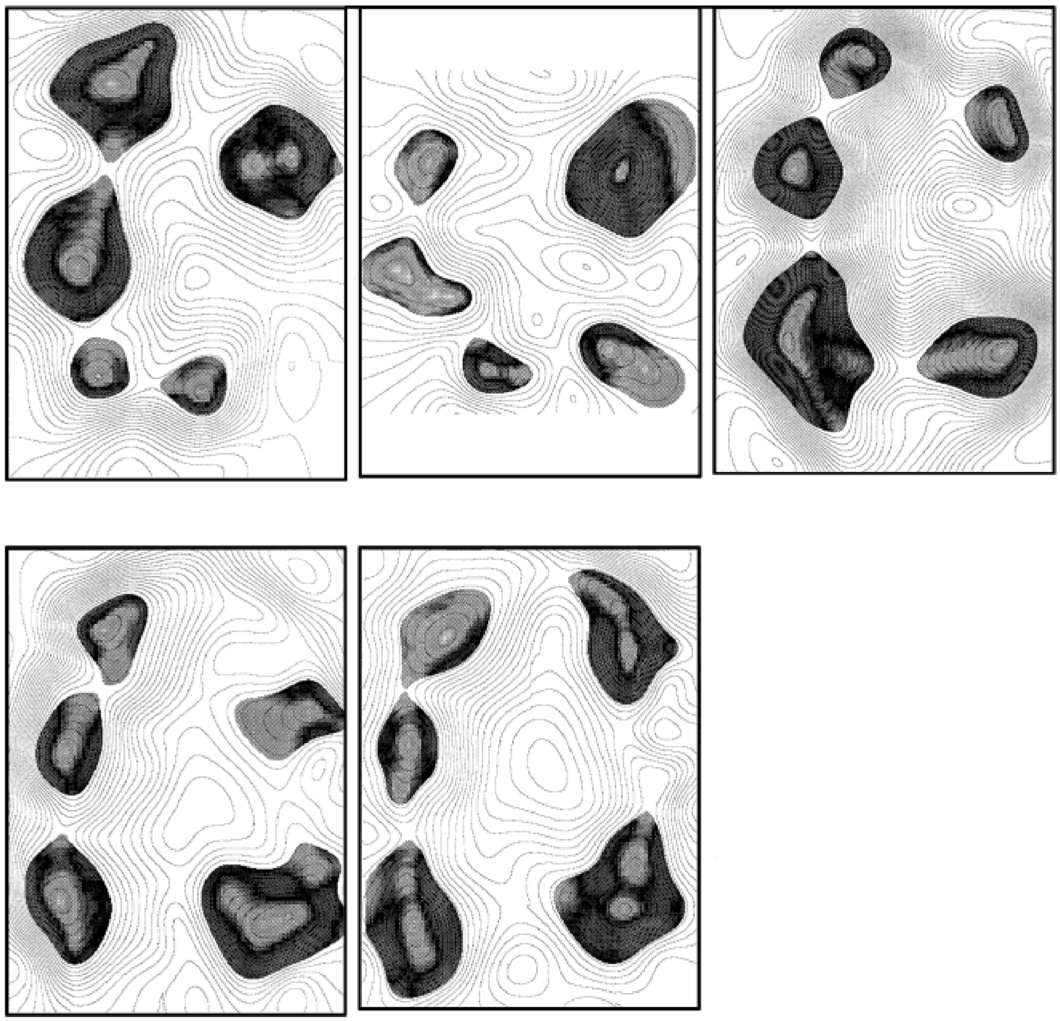

Fig. 2. Contour lines and slopes of cusps for each tooth (upper left to lower right): *Afropithecus, Dryopithecus, Gorilla, Pan, Pongo.* Steeper slopes are represented by darker shading.

for individual cusps were then calculated by summing elevation cells and averaging slope cells, respectively. GRASS also calculates descriptive statistics to characterize the spatial distribution of slope and aspect values for the cusps. Such data may prove to be valuable for comparisons of cusp form within and between individuals and species.

Basin drainage and volume

GRASS also provides other tools that might be valuable for the characterization and comparison of occlusal surfaces. For example, the way food or liquid might accumulate or drain over a tooth's surface is readily modeled by GRASS commands designed to simulate the flow of water and sediment across a terrain. Such routines promise to shed considerable light on tooth function.

We used the GRASS command r.watershed to delineate drainage patterns across the occlusal surface, assigning each cell a value that reflects how many other cells drain into it. By reclassing the resulting raster layer to show only those cells with a value of 100 or higher, the primary drainage routes can be displayed (Fig. 3). Basins can

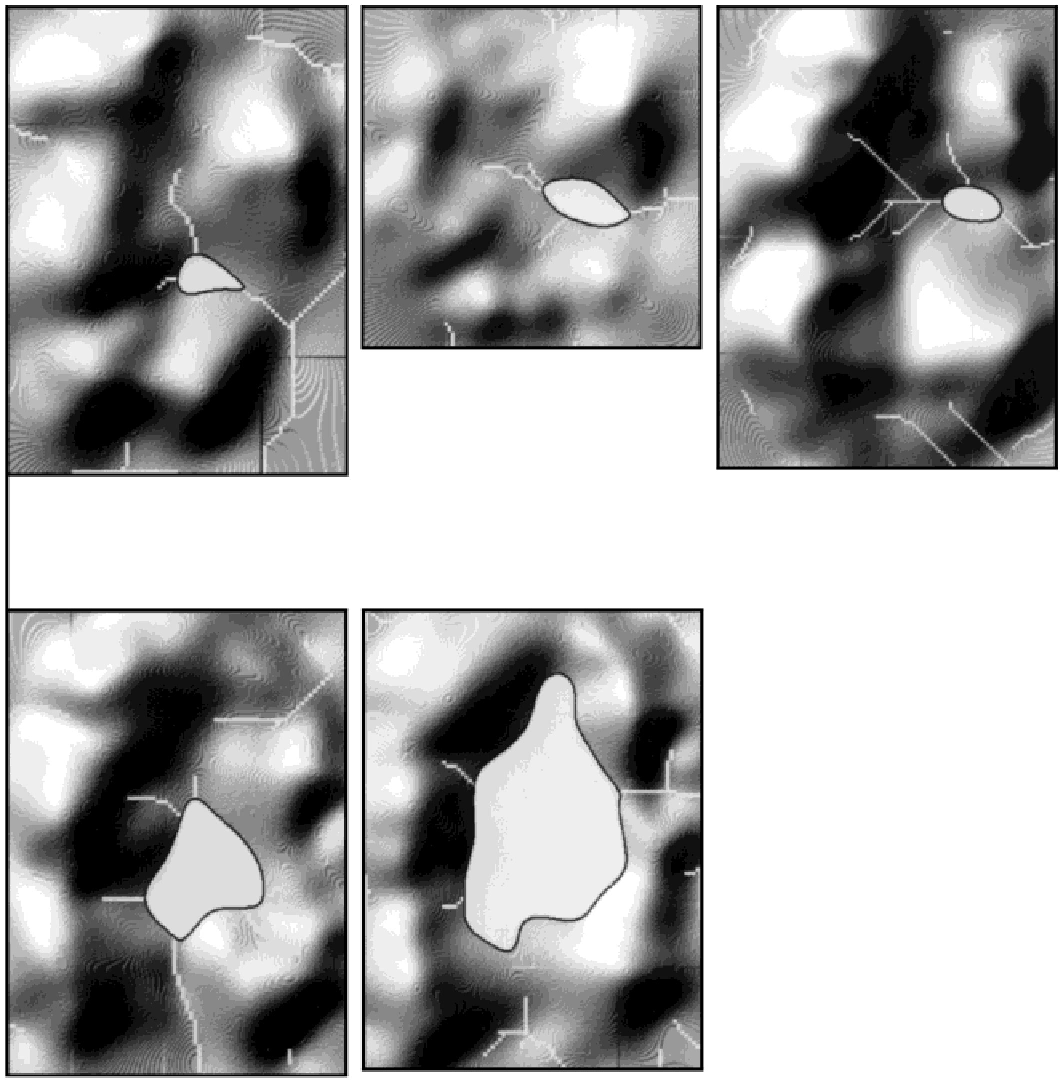

Fig. 3. Combined shaded relief maps with drainage and basin information (upper left to lower right): *Afropithecus, Dryopithecus, Gorilla, Pan, Pongo.* Lines represent drainage routes, and enclosed shapes represent fluid accumulations or basins.

be defined as those areas where fluid would accumulate. When r.watershed encounters such an area, it determines the lowest point of overflow and continues delineating the drainage. GRASS can then "fill" the basin and measure its volume (Fig. 3).

DISCUSSION

Methods described here can be used to model and compare tooth occlusal surfaces in three dimensions. GRASS can interpolate dental surfaces from three-dimensional point coordinates and determine numerous attributes of those surfaces, including cusp area, volume, slope, and aspect. Modeling dental topography using GIS also allows us to examine surface characteristics such as drainage and accumulation of fluid. Resulting data can be used to accurately characterize teeth in three dimensions, and to compare taxa in both functional and phylogenetic analyses.

Because of limitations to the resolution of the digitizer and the geometry of the stylus used in this study, thin-plate splining was necessary to create a model of each surface. We expect that a device capable of collecting points with greater precision, such as a high-resolution laser digitizer (Rosenberger and Calvo, 1998), would eliminate the need for interpolation.

Methods described in this article also have important applications beyond dental morphology. GRASS holds the potential to model and compare a broad range of complex surfaces, including skulls, joints, and other biological structures.

ACKNOWLEDGMENTS

We thank Drs. William Stanley and László Kordos for allowing us to cast specimens in their care. We thank Dr. Mark Teaford for providing us with the *Afropithecus turkanesis* cast. Computer systems were provided by Intergraph Corporation and SUN Microsystems.

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